NESS Project Final Report

European Research Council
Executive Agency

Project No: 279068

Project Acronym: NeSS

Project Full Name: Listening to the Future: Next-generation Sound Synthesis ?through Simulation

ERC-SG

Final Activity Report

Period covered: from 01/01/2012 **to** 31/12/2016

Start date of project: 01/01/2012

Duration: 60

Principal Investigator name:
Dr. Stefan Bilbao

Date of preparation: 30/12/2016

Date of submission (SESAM):

Report submitted by:
THE UNIVERSITY OF EDINBURGH

Final Activity Report

GENERAL INFORMATION

Project No.:	279068
Project acronym:	NeSS
Project full name:	Listening to the Future: Next-generation Sound Synthesis ?through Simulation
Project starting date:	01/01/2012
Project duration [months]:	60
Principal Investigator name:	Dr. Stefan Bilbao
Host Institution name:	THE UNIVERSITY OF EDINBURGH
Date of submission:	

Final Activity Report

Summary of the major project achievements over the entire lifetime of the project

The information provided in this section will only be available to ERC staff, to members of the ERC panels, and to the Scientific Council

Explain in a clear manner the work performed during the entire lifetime of the project along the main objectives/activities of the project listed in the Description of Work (DoW). Please indicate the publications linked to these objectives/activities.

Please specify the outcome in terms of:

- research and technological achievements along the main objectives/activities (in line with the DoW)

Research under the NESS project can be divided into three major groupings: 1) algorithm design, 2) code parallelisation, acceleration and 3) optimisation, and creative work. The associated researchers are indicated by initials: see list below under "establishment and/or consolidation of the research group and team composition."

1) Algorithm Design (SB, BH, RH, CD, MD, AT, CW): Work at the level of algorithm design involves basic system modelling, in terms of model choice and its suitability for sound synthesis, the design of time-stepping methods, and finally prototyping in Matlab. Work at this level may be described with reference to various strands, or instrument/system types, as follows, indicated by labels R1 to R8. A brief overview of the time-stepping methods employed in this project may be found at
http://www.ness.music.ed.ac.uk/project#3

R1. Brass instrument modelling (RH, SB): A complete framework for brass instrument synthesis has been developed, which includes various novel features, including design freedom with regard to the bore profile, the design and placement of valves, as well as complete control over lip/blowing parameters as well as time-varying control over valves. Later work, still in progress, involves the embedding of such an instrument in a three-dimensional acoustic enclosure, and the modelling of nonlinear effects of shock wave propagation in the bore. See the NESS brass page at
http://www.ness.music.ed.ac.uk/archives/systems/brass-instruments-2

R2. Electromechanical Effects (MD, SB): In addition to direct sound synthesis, another use of physical modelling has been the emulation of electromechanical effects units, and in particular the plate reverberation unit (MD), which is suitable for real-time use, as well as spring reverberation. See the NESS electromechanical effects page at
http://www.ness.music.ed.ac.uk/archives/systems/electromechanical-instruments

R3. Bowed String Instruments (CD, SB): A novel fine-grained model of bowed string dynamics has been developed, with the modelling of string vibration in both polarizations, as well as a much more detailed model of bow dynamics than previously available, including collision interactions. Also included are collision interactions between the fingers and string, and the string and a backing fretboard. Another novelty is the modelling of bow control explicitly through force signals, leading to new insights in terms of the parameter space of playability. See the NESS bowed string synthesis page at
http://www.ness.music.ed.ac.uk/archives/systems/bowed-string-instruments

R4. Percussion Instrument Modeling/Cymbals and Gongs (AT, SB, MD): Percussion instrument modelling involves what are perhaps the most numerically difficult problems in NESS, due to the problem size, as well as the variety of strong nonlinearities which occur, and which are crucial to achieving high-quality synthetic sound output. A full system of instruments is now in place, and these are modelled in 3D; these include: basic gongs, timpani drums, as well as snare drums. The snare drum in particular has been approached using a detailed collision model for the snare/membrane interaction, leading to characteristic noise-like effects. Further developments have been in the direction of simplified modal nonlinear percussion instruments, which may be suitable for real time implementation (MD). See the NESS percussion instrument modelling page at http://www.ness.music.ed.ac.uk/archives/systems/3d-embeddings

R5. Wave-based room acoustics simulation (BH, SB, CW): The state of the art in wave based room acoustics modelling has advanced significantly under the NESS Project. A full system is in place now, allowing for a) modelling of spatially-varying and frequency dependent wall conditions, b) arbitrary geometries, and c) viscothermal effects in air. Perhaps the most significant step was in moving from finite difference time domain methods, defined over regular grids, to finite volume methods, allowing for detailed modelling of wall conditions in a numerically stable manner. The system in place now forms the basis for the subsequent ERC-funded Proof of Concept grant WRAM (Wave Based Room Acoustics Modeling). See the NESS wave-based room acoustics page at http://www.ness.music.ed.ac.uk/archives/systems/virtual-room-acoustics

R6. Modular Synthesis Environments (SB, CW): Various modular environments have been developed over the course of NESS. The zero code was a basic connected plate model, accompanied by spring-like connections; the zero point one code was a modification allowing for audio input. Later in the project, we developed the soundboard code, allowing for string/plate connections, and finally the net1 code, allowing for rattling elements, employing new methods for dealing with collisions developed throughout the course of NESS. In all cases, the user has complete control over the instrument designs, through the choice of canonical elements such as plates, strings, membranes or bars, as well as connections, which may be nonlinear and of various types (rattling, spring-like). The user also has control over the score, which may consist of strikes, plucks, bowing gestures, as well as audio input, in which case the environment is used as an audio effect. All environments have an in-built numerical stability guarantee, through numerical energy balance principles. See the NESS modular synthesis page at
http://www.ness.music.ed.ac.uk/archives/systems/modular-environments

R7. Guitars (SB, MD): Guitar modelling has been extended considerably under NESS, to incorporate more realistic features of finger/string dynamics, as well as very detailed control of the finger/string interaction. Most important here has been explicit collision modelling of the interaction between the string and the fretboard, as well as between the finger and the string. This has led to a very detailed timbre space, allowing for characteristic rattling of strings, playing on the harmonics, etc. Control of the fingers is time-varying, allowing for the emulation of complex gestures such as barre chords, tapping etc. A further development (MD) has been the introduction of geometric nonlinear effects in the strings themselves, allowing for pitch bending effects. See the NESS guitar page at http://www.ness.music.ed.ac.uk/archives/systems/guitarfretboard-interactions

R8. Antialiasing techniques (SB+Aalto University): A new direction under NESS, and developed in conjunction with project partners at Aalto University of Technology, has been a set of numerical approaches to the reduction of aliasing effects under nonlinear audio processing. Though only tangentially related to physical modelling synthesis as yet (the main application is to virtual analog circuit modelling), the techniques do address one of the main shortcomings of the techniques developed under NESS, in that there has not been, as yet, any approach to dealing with the difficulties of aliasing.

2) Code Parallelisation, Acceleration and Optimisation (JP, PG, AG, LS, CW, KK, AM). The project was set up with GPU parallelisation at its core. During the project we also utilised multi-core, vectorisation and traditional HPC as well as combinations of hardware technologies and optimisation techniques as required. In general, the aim of employing these types of hardware and techniques was to maximise the performance of the codes, and this was achieved, allowing the composers to deliver musical pieces much faster and with more features than previously available. It should be noted that the 3D room acoustics simulation was also ported to Archer, the UK's main academic supercomputer, where it executes slower than on GPUs, but this allows to simulate rooms that are too big to accommodate in our GPU system. More information is available on the NESS acceleration webpage, available from
http://www.ness.music.ed.ac.uk/acceleration

The NESS codes were developed in Matlab, then ported to C++, optimised and parallelised. All musical synthesis codes are available from the NESS web-based user interface; they are as follows: Zero code, Zero Point 1 code, Multiplate, Modal Plate, Soundboard, Guitar, Net1, Bowed string, Brass. Of these codes, Brass is available as a free download. For very few users who have explicitly asked for it, we also allowed command-line access to all the musical synthesis codes, by giving them access to the NESSGPU computer.

In terms of implementation, the following list gives the capabilities of each code. All musical synthesis codes can run on multi-core (M) or single-core (S) computers (with commensurate performance), and the code allows to fall back to this if GPU (G) and/or multi-core are not available. Advanced vector extensions (V) were used in some cases. Archer, the UK Supercomputer was also employed (H).

Zero: G
Zero Point 1: G
Multiplate: G, M, V
Modal plate: M,V
Soundboard: M
Guitar: M
Net1: M
Bowed string: M
Brass: S,V
Room acoustics:G,H

3) Creative Work (TW,GD,GS+others): There were approximately 15 visits by composers over the duration of the NESS Project. In all cases, the musicians worked with the team in a (usually) one-on-one workshop setting in order to learn the use of the systems, as well as to provide feedback. Six pieces were completed over the course of NESS, using the entire suite of tools, and making full use of multichannel capability. A list of these pieces, as well as performances to date, is provided in Section A6. Stereo reductions of the pieces are also available online at
http://www.ness.music.ed.ac.uk/music-and-tools/music

- novel and/or unconventional methodologies

Passive representations: One of the modeling principles employed throughout the NESS project has been a rather unconventional one, at least in the setting of simulation methods: that of an underlying passive representation of a given dynamical system. That is to say, the system under study is viewed, always, as satisfying an energy balance relating the rate of change of the stored energy of the system to dissipated power and to supplied power. The system is passive if the stored energy is a non-negative function of the state, and if the dissipated power is non-negative as well. In the NESS project, then, the representation is such a form is a necessary prelude to any numerical design, as it guides the form of the chosen design so as to mimic such a property in discrete time. This design principle has led to new classes of numerical methods for virtually all the systems under study in NESS, including those with strongly nonlinear behaviour, coupled systems, and those for which loss characteristics are of a nontrivial form. Such a representation can be viewed as an extension of the Hamiltonian representation of a lossless unforced system.

Energy-balanced numerical methods: Following from the notion of a passive representation of a given system, one may then proceed to a numerical time-stepping method. A standard approach, at least for Hamiltonian systems, has been to make use of a direct transfer of the expression for stored energy to discrete time---this leads, invariably, to implicit numerical methods, which are usually unsuited to very large scale simulation, and certainly not for audio applications, where perceptual artefacts due to numerical dispersion will be severe. The benefit of such an approach is an unconditional guarantee of numerical stability. Under NESS, we have taken a wider view of the definition of numerical energy, and indeed, it may be extended considerably to develop conditionally stable numerical methods which are far more efficient, and which possess much better properties in terms of numerical dispersion. Such methods are new in the general setting of conservative or energy-balanced numerical simulation techniques.

Finite volume approaches to 3D room acoustics simulation: Though wave-based simulation methods for room acoustics problems have been around for some time (they date back to the mid 1990s), most published studies dealt with the behaviour of a given FDTD scheme over the problem interior. In particular, there was no solid theory of the termination of the scheme---an all important consideration in room acoustics, given that most of the problem complexity lies with the boundary conditions, which are defined over an irregular geometry, and are of a complex frequency-dependent form, and variable from one boundary location to another. The FDTD framework did not allow for such analysis. A major development under NESS has been the theoretical shift towards finite volume time domain methods (FVTD). Such methods reduce to FDTD over regular arrangements of cells (the interior), and thus do not introduce extra complexity in terms of parallelisation over the largest part of the simulation. But at the boundaries, it becomes possible to depart from the regular arrangement of cells to better fit the problem geometry---this has quite nonnegligible ramifications in terms of the computed decay times for rooms, and also in terms of the coherence of computed responses, which are far superior when fitted cells are used in FVTD. The largest benefit, however, is that FVTD fits very easily into the energy-based stability checking machinery used in NESS, and is able to take into account arbitrary passive wall terminations. The resulting system under NESS is what could easily be described as the state of the art in wave based room acoustics.

Modified Equation Techniques: A new framework for the design of high accuracy solvers for the wave equation has been developed, with special utility in reducing numerical dispersion in room acoustics solvers. Such methods are based upon novel extensions of modified equation techniques, allowing for the use of very sparse two-step methods---which are minimal in terms of memory usage, and ideal for very large scale parallelisation. A complete framework has been developed, allowing for conveniently expressed parameter constraints for both order of accuracy and stability, as well as explicit control over the size of the stencil (and thus the operation count).

Collision Modeling: An unforeseen development under NESS was the development of algorithms to model collisions across a wide range of scenarios in musical acoustics---these include simple interactions such as the hammer/string or mallet/membrane interaction, but also more complex interactions such as the lip/mouthpiece collision in brass instruments, the string fretboard interaction in guitars, finger/string interactions in guitar and bowed string instruments, the bow/string interaction, and finally the snare/membrane interaction in the snare drum. The models we have developed are based on the use of a penalty potential to model interpenetration, but numerically, they fit well into the energy-balanced framework used to prove numerical stability of a given design. The use of these new techniques led to a wide range of new codes, including the guitar and net1 modular environment.

Antialisasing in Nonlinear Audio Modeling; Another unforeseen development under NESS was thee development of techniques to reduce/remove aliasing effects under nonlinear audio processing, enabling operation at audio rates (as opposed to at oversampled rates). This work was in conjunction with NESS Project partners at Aalto University of Technology.

Hybridized Parallel Codes: An interesting technique applied for performance improvement of codes is to use various means of parallelisation. Each iteration of the Multiplate 3D code uses: GPU for the air around the plates; a core of multi-core CPU per plate; and vectorisation units, also for each plate. The code also employs mixed numerical precision and efficient data storage techniques to improve its performance.

- inter and cross disciplinary developments

The NESS Project was cross disciplinary by design, and built around linked strands of inquiry in numerical method design and acoustics, parallel computing, as well as creative work. Thus all work under the NESS Project was cross disciplinary. Of the three areas covered by NESS, mainly algorithm design, parallel computing and the creative use of the codes, the first served as the link among the three. In particular, cross-disciplinary links were:

Algorithm design <--> parallel computing: the constraints in the parallel implementation informed algorithm design greatly, particularly with regard to the major issue of linear system solvers, as well as iterative methods such as Newton Raphson, which play a central role in all nonlinear codes. Such methods are not easily parallelised, and thus the algorithm team went to great pains to either reduce complexity in these cases or sidestep their use. In another instance, a code was sped up by more than 100 times by restructuring slightly and replacing a linear search operation by a binary search.

Algorithm design <--> creative work: interaction with musicians here informed various simplifications to standard parameter sets for physical models---a major choice to be made her, based on feedback from musicians was whether to employ physical or perceptual parameters in instrument design/score generation. We opted for the former. Another had to do with modes of input---fairly early on it became clear that, for certain instruments such as percussion, striking/plucking input was not sufficient to get the range of timbres desired by the musicians, who often wanted steady timbres. This was remedied mainly through the use of audio input, thus expanding the use of physical models from synthesis tools to audio effects. Other new issues emerged, having to do with normalisation in a multichannel setting, a previously unstudied problem.

- knowledge and technology transfer

NESS was designed as a research project exploring the fundamentals of physical modelling synthesis algorithms, as well as parallelisation, and with some additional work, at the level of knowledge transfer through the explicit direct collaboration with musicians, which did not constitute a direct research output. Knowledge transfer through commercialisation activities did not form an intended part of NESS; and yet, as time progressed, several new opportunities presented themselves. Knowledge transfer activities can be classified as follows:

Web-based interface and software releases: From early in the project (2012), there was the need for a simple way for musicians to access and experiment with NESS codes. A simple web interface was built, allowing the user to upload instrument and score files, and then download resulting sound output. The system, which is still running, operates under a registration system from the University of Edinburgh, and is free of charge. In addition, one package, brass, was fast enough to be released as a standalone software package, and may be downloaded from the NESS website. All materials, as well as extensive user documentation and example score/instrument files, are available at http://www.ness.music.ed.ac.uk/music-and-tools

Real-time implementations and audio unit plugins: Real time performance of the physical modelling implementations, as well as an investigation of control and UI design were not part of the original remit of the project, for the simple reason that it would have been premature, and perhaps limiting in terms of the scope of models that were desired to be examined. Towards the end of the project, the team began looking at certain codes that were fast enough for real time implementation. These include a plate reverberation audio unit plugin (CW and MD), which has undergone beta testing and which will be released commercially in 2017. A new plugin, built around the net1 code (CW and SB) is under development, and will be released for beta testing in 2017. Both products, and subsequent releases, will be released through the spinout company Physical Audio, formed by CW, SB and MD in 2016. See the website at http://www.physicalaudio.co.uk/

Room acoustics modelling system: A distinct commercial development, now supported by ERC Proof of Concept funding as the WRAM Project (Wave based Room Acoustics Modeling) is concerned with highly accurate wave-based simulators for real-world problems in room and architectural acoustics, and, possibly, applications in virtual reality. The simulator is necessarily out of real time, due to the very large computational requirements, and is based directly on NESS Project work in 3D acoustics. The WRAM team (BH and SB) will be building a prototype system, and exploring different modes of commercialisation, while working closely with various industrial partners, who will provide test case data as well as feedback. By the project termination in June 2018, we hope to have a spinout company launched.

- enhancing the immediate research environment

Beyond the establishment of the Acoustics and Audio Group (AAG) at the University of Edinburgh (see below), the immediate research environment has been enhanced in various ways.

There is a strong group ethos, to the extent that the first three PhD graduates of the NESS Project have continued on to postdoctoral work in the AAG. CW, who graduated in 2014, rejoined the project as a postdoctoral RA, in its final stages in order to begin the new work of porting codes to real-time, in anticipation of commercial releases through a new spinout company, formed with SB and MD. AT is currently a PDRA, working in the AAG in the area of micromechanical microphone design. BH stayed with the NESS Project as a PDRA, and will continue on through its successor, the WRAM Project, which resulted from a successful ERC Proof of Concept bid. In addition, our important relations with partners under NESS have led to group growth as well---MD, a PhD student at the Ecole Nationale Superieure de techniques Avancees, in Palaiseau, France, joined the AAG and the NESS Project as a Newton International Fellow, funded by the Royal Society and British Academy in 2015. New funding bids are in progress to support the continued activities of NESS project members in the AAG, including MD, CW and RH.

The publication ethos of the NESS Project has been perhaps its strongest suit; all NESS staff members have published extensively, in both peer-reviewed journals, as well as at international conferences. The median number of publications for all NESS PhD students is approximately 10. All PhD students have led their own presentations, have led the development of filmed instructional videos, and have led workshop activities with visiting musicians.

EPCC benefited greatly from the acquisition of knowledge in programming GPUs and programming linear model solvers. Inter-disciplinary research is at the core of the Centre, and EPCC acquired some level of expertise in the domain of musical acoustics. NESS is a great success story that has already been demonstrated effectively to highlight the benefits of high-performance computing and show-case EPCC's skills. These are excellent, exploitable results for EPCC, a self-sustained Centre in the University of Edinburgh, and will aid future business generation. For example, EPCC is currently working on an EC project proposal, generated directly from NESS. The project also fostered the co-supervision of two PhD students, an activity that is valued in the Centre.

- establishment and/or consolidation of the research group and team composition

The NESS Project has served to greatly strengthen the Acoustics and Audio Group (AAG) at the University of Edinburgh. The AAG is now in the final stages of preparing a bid for Centre status within the University of Edinburgh, and has a large infrastructure, including dedicated laboratory space, a dedicated seminar series in Musical Acoustics and Informatics, and a dedicated MSc programme in Acoustics and Music Technology, which has grown considerably during the course of NESS, from 6 students in 2009/2010 to 17 in 2015/2016. See the AAG webpage at http://www.acoustics.ed.ac.uk

The international collaborations built into the NESS Project (with the Aalto University of Technology, and the Ecole Nationale Superieure de Techniques Avancees) have expanded to include other partners (the Universite de Paris VI, as well as the CNRS Marseille), and have served as a means of consolidating the position of the AAG in an international setting, through a great number of joint publications.

The NESS team at Edinburgh will be largely responsible for organising the 20th International Conference on Digital Audio Effects in Edinburgh in 2017 (www.dafx17.eca.ed.ac.uk). The core research group formed under NESS has served as a magnet to attract newer staff and students to both the Acoustics and Audio Group (AAG) and the Edinburgh Parallel Computing Centre (EPCC) at the University of Edinburgh. See, in particular, CD, MD, LS in the staff list below. Also, the teaching replacement assigned to cover the PI's teaching duties has been made permanent, further increasing the strength of the AAG. NESS project activities have been integral to securing new funding bids, including the MSCA-ITN BATWOMAN, in which the AAG is a partner, as well as a highly competitive Newton International Fellowship from the Royal Society/British Academy (see MD in staff list below).

Staff members over the duration of NESS (indicated henceforth by initials), and their respective tasks were:

SB: Stefan Bilbao (Principal Investigator, AAG). Tasks: general project oversight, algorithm design, supervision of PhD students, management of research visits by visiting composers.

KK: Kostas Kavoussanakis (Project Manager, EPCC). Tasks: management of EPCC team members, including scheduling and chairing of project meetings (every two weeks), management of equipment purchase, scheduling of programming tasks and management of deliverables schedule, in conjunction with SB.

AG: Alan Gray (Technical Reviewer, EPCC). Tasks: internal oversight of project appointed by University of Edinburgh. Deputy chairing of project meetings.

JP: James Perry (GPU software engineer, EPCC). Tasks: programming in C/CUDA, correctness/benchmark testing, writing technical papers and documentation, workshop activities with composers.

AM: Adrian Mouat (GPU software engineer, EPCC). Tasks: programming in C/CUDA, correctness/benchmark testing.

PG: Paul Graham (GPU/interface software engineer, EPCC). Tasks: programming in C/CUDA, correctness/benchmark testing, writing technical papers and documentation, workshop activities with composers. Development of 3D demo materials.

CW: Craig Webb (RA, formerly PhD student, AAG/EPCC). Tasks: C/CUDA programming, technical paper writing and presentation at conferences,, as well as real time programming.

BH: Brian Hamilton (RA, formerly PhD student, AAG). Tasks: algorithm design, MATLAB, C and CUDA programming, technical paper writing and presentation at conferences, workshop activities with composers. BH's student funding from NESS terminated in February 2015. He was hired as a post-doctoral research assistant on NESS from December, 2015, and will continue on after NESS as a postdoctoral RA on the ERC PoC WRAM (wave-based Room Acoustics Modeling) Project, which broke ground in December 2016.

AT: Alberto Torin (PhD student, AAG). Tasks: algorithm design, MATLAB programming, technical paper writing and presentation at conferences, workshop activities with composers. AT's student funding from NESS terminated in February 2015.

RH: Reginald Harrison (PhD student, AAG). Tasks: algorithm design, MATLAB programming, technical paper writing and presentation at conferences, workshop activities with composers.

CD: Charlotte Desvages (PhD student, AAG). Tasks: algorithm design, MATLAB programming, technical paper writing and presentation at conferences, workshop activities with composers. NB: CD joined the project as a new member, working on core NESS algorithm design activities. CD has recourse to UoE/scholarship funding, and was paid by the NESS budget between September and December 2016. Some travel costs have been allocated to CD, for presentation at conferences.

MD: Michele Ducceschi (Royal Society Newton Internation Fellow, AAG). MD oined the project as of 04/15, and is working on plate and string based synthesis, including real time programming. MD is not paid by the NESS budget.

LS: Larisa Stoltzfus (PhD student, EPCC). A newer addition to the team as of September 2015, concerned with code portability for large parallelised room acoustics codes. LS has recourse to UoE/scholarship funding, and is not paid by the NESS budget.

Visiting composers over the course of NESS include:

GD: Dr. Gordon Delap, National University of Ireland Maynooth.

TW: Trevor Wishart, University of Durham.

GS: Gadi Sassoon, independent composer.

CC: Chris Chafe, Stanford University.

VL: Victor Lazzarini, National University of Ireland Maynooth.

IM: Iain McCurdy, National University of Ireland Maynooth.

RC; Ricardo Climent, University of Manchester.

- others

No others.

Publishable brief summary of the achievement of the project

This section, which should not exceed 1 page (approx. 600 words), might be used for dissemination of the project progress/results to the general public/scientific community. For this reason, please do not reproduce here the project abstract, which is already available in CORDIS.

Stand alone description of the project and its outcomes

The aim of the NESS Project has been, in short, to extend the boundaries of computer-generated musical sound. This has been done through an appeal to physical models of sound-producing systems and acoustic spaces, simulation algorithm design, as well as large scale parallel computing. Systems have been chosen from across the range of acoustic musical instruments, including the brass instrument family, bowed strings, guitars, and percussion instruments; beyond this, new modular instrument construction frameworks have been developed, allowing the musician complete freedom in the design and performance of a virtual musical instrument. A related research question has involved the rendering of such sound in three-dimensional environments, leading to very large computational problem sizes, and the necessity of working in specialised parallel hardware (graphics processing units). Such work has led, ultimately, to a general framework for wave-based modelling of room and architectural acoustics. A web-based interface to a suite of synthesis codes has been developed, and has been used by visiting musicians in order to generate experimental multichannel pieces of music, which have been performed internationally on many occasions.

Overall assessment of the achievements and success of the project

The information provided in this section will only be available to ERC staff, to members of the ERC panels, and to the Scientific Council

To what extent have you achieved your objectives?

It is useful to characterise the objectives in terms of the main strands of work: algorithmic, parallel computing, and creative:

Algorithmic work: We have largely achieved our stated objectives. The progress has, of course, been uneven, as was anticipated. In some cases, we have surpassed the objectives as stated. In others, we have changed gears, mid project, to follow new directions which proved to be fruitful. It is useful to refer here to the major categories of results, listed as R1 to R8 in “research and technological achievements and the impact and use of them.” Collision modelling, which became a major new direction of the NESS Project, and which led to two new areas, R3 and R7 in the section “research and technological achievements and the impact and use of them” as well as new developments under R4 and R6. The research area R8 was entirely new, and resulted from joint work with the NESS Project partner Aalto University of Technology.

It is useful to refer to the tasks as stated in the original proposal from 2010, which were originally numbered T1 through T6. These should be compared against the project results R1-R8, listed in the section “research and technological achievements and the impact and use of them.”

T1: Brass Instruments: corresponds to result R1. Most objectives achieved. Shock wave modelling is still in progress, but a preliminary publication appeared at the International Congress on Acoustics in 2016.

T2: Electromechanical Instruments: This research direction was largely superseded by work on collision modelling under R3 and R7, and electromechanical effects under R2.

T3: Nonlinear Plate and Shell Vibration: subsumed into R4, which became a much larger area, and included nonlinear models for membrane instruments, coupled with the 3D field, as well as snare drums.

T4: largely subsumed under R6, resulting a large variety of modular construction frameworks, including new collision-based connection elements.

T5: 3D Room Acoustics Modeling: corresponds to result R5. All objectives achieved. Work done forms the basis for new ERC Proof of Concept Project WRAM.

T6: Embeddings and Spatialisation: subsumed to result R4. All objectives achieved.

In terms of publication output, in the original proposal, we projected three publications for each area (T1-T6), or a total of 18. The actual output from the NESS project was much larger, with 19 journal articles, and more than 50 conference proceedings articles, as well as a book chapter.

Parallelisation work: The objective for parallelisation was to take advantage of multi-core and GPU technologies in order to maximise the performance of computationally intensive problems. We achieved this objective to the extent allowed by the nature of the codes, and extended our approach to include explicit vectorisation and traditional HPC. We also applied numerous optimisation techniques beyond porting the codes to different architectures. In general, the codes run between 12 and 220 times faster than the Matlab models, with the improvement increasing broadly in line with the computational complexity of each code. A different dimension was offered by the abundant memory available on the UK's supercomputer, which enabled much bigger 3D-room simulations than what was possible on our GPU host.

Creative work: The final results were very satisfying. In the end, six pieces were produced under NESS---two in stereo, one in an eight-channel format, two in a sixteen channel format, and one for 32 channels. The full range of NESS codes was used, from brass, to the modular codes zero, zero point one and net1, to 3D percussion codes. These have been performed internationally at festivals and symposia on approximately 25 occasions to date.

What are the most imortant conclusions of your research?

The main conclusions are the following:

1) The range of sound which can be produced using physical modelling approaches is immense, and represents the next frontier for virtual audio.

2) The simulation of large acoustic spaces in 3D, though a very large computational undertaking, is becoming possible at audio rates on parallel hardware. In the near future, we expect to see a paradigm shift, with ray-based acoustics rendering completely replaced, in a timeframe of 5-10 years.

3) The control of virtual musical instruments is at least as difficult to learn and master as that of conventional acoustic musical instruments. Thus control strategies form a next goal.

4) Parallel architectures offer great opportunities for acceleration of audio synthesis codes, but must be used judiciously; often different modes of parallelisation (and perhaps hybrid techniques) are most useful for a given system.

To what extent have you gone beyond the state of the art?

It is fair to say, at this point, that the NESS Project has been the most far-reaching investigation into computer-generated sound ever attempted. The state of the art in 2012 for physical modelling sound synthesis, and, to a certain extent wave-based room acoustics modelling was firmly rooted in tools which have their origin in audio signal processing, and not in computational physics. This was partly historical, and follows from the methodology of earlier, non-physical sound synthesis, and also partly due to efficiency concerns. For physical systems of increasing complexity, however, such tools become an increasingly awkward match. With NESS, we feel as though we have shifted the general orientation of this field towards the latter, allowing for a much larger range of possible applications, and access to much finer features of musical instrument and room modeling. Such improved modelling leads, inevitably, to higher quality and more realistic synthetic sound. This has been demonstrated definitively in the musical works created during the course of this project.

This change in orientation can be seen in all of the model systems approached under NESS, for which we have, now, a much more flexible approach to synthesis, making far fewer simplifying hypotheses, and allowing musical systems to exhibit the range of interesting unpredictability characteristic of true acoustic sounds. It can be heard in multiphonics in virtual brass instruments under half-valved conditions, in bouncing and scraping of bows, and in crashes of gongs. Going beyond this, we now have a complete system for rendering such systems in 3D, and, even further, a full system for wave-based room acoustics, incorporating all of the fine geometrical and material properties of real spaces.

The extent to which a range of parallel computing architectures and techniques have been combined and made to interoperate effectively to solve the range of complex problems that arise in this area is novel. The NESS parallelisation team successfully combined an array of established techniques to parallelise and optimise the codes; it is this combination of techniques, applied to GPUs (and traditional HPC), to generate sound and simulate room acoustics that is new.

What is the impact of the project (within the scientific community and on society)?

The publication output of the NESS Project has greatly exceeded expectations; a target, for the PI, was 18 pieces of published work throughout the course of the project. The current total is now more than 75, not including several new pieces of work under review or in preparation. Of the 19 journal publications produced so far under the NESS Project, a large fraction appear in esteemed publications such as various IEEE Transactions and the Journal of the Acoustical Society of America.

In addition, the PI has given three keynote lectures at international symposia and conferences, and has presented work at university laboratories on 17 occasions during the course of the NESS Project. Within the international community, we now have solid publishing relationships with groups at the Aalto University of Technology, the CNRS Marseille, ENSTA Palaiseau, and the Universite de Paris VI. The NESS Project has served as the springboard for hosting the 20th International Conference on Digital Audio Effects in Edinburgh in 2017.

Publication output for the parallelisation work has also exceeded expectations. Of the seven publications involving EPCC, the most notable was published in the International Conference on Parallel Computing in 2015, describing the application of hybrid parallelism to the multiplate code.

From an artistic point of view, the NESS Project, through open access to its web-based interface to the synthesis engine, has led to the creation of new multichannel pieces of music which have been performed widely at international festivals and symposia---see the list of performances under “Other Outputs.”

From a commercial point of view, members of the NESS team are currently engaged in developing commercial products for suitable parts of the NESS code corpus, and are building commercial enterprises on two fronts, corresponding to real time synthesis, and to architectural room acoustics software. See the section on Knowledge Exchange for more information.

How effectively has the project helped you start or consolidate your research group? (for Starting Grants/Consolidators Grants only)

The Starting Grant has proved to be an extremely effective means of consolidating a research group, particularly because of the long duration---freeing the hands of the PI considerably to think about the longer term future of the immediate research environment. This was aided by the light touch reporting requirements of the ERC.

For more on the specifics of the enhancement of the immediate research environment, see the relevant sections below.

How well have you been supported by your Host Institution?

The general level of support given by the University of Edinburgh was sufficient for the purposes of

NESS. I was given the time to do the research, and largely relieved of teaching duties. As of 2016, the staff member hired as my teaching replacement has been made permanent, showing a commitment of the University to the longer-term future of the Acoustics and Audio Group.

At the more immediate level, support was divided roughly evenly between two administrative units within the University of Edinburgh, the Edinburgh College of Art (ECA), and the Edinburgh Parallel Computing Centre (EPCC), until 2016 a part of the School of Physics and Astronomy, and now an independent unit.

ECA has provided support for advertising of positions and interviewing of candidates, and also for purchasing of equipment, and the processing of travel claims. It has also provided space, technical support and some additional funds related to a newly designed multichannel listening space. It has also provided funds for the filming and editing of a set of short videos which will be used in order to showcase NESS project results. It has also provided some additional travel funds both for the PI and for students in the NESS team. In terms of computing support, ECA has agreed to host the NESS GPU servers beyond the end of the NESS Project, allowing for great additional value to the project beyond the lifetime of the project itself. A multichannel studio space, for creative work, was provided by the Edinburgh College of Art for the duration of the project.

EPCC and the School of Physics have provided free of charge the following: administrative support (including financial accounts, staff contracts and timesheets, and travel arrangements); technical support (installation of software licences as well as procurement, deployment and maintenance of specialised GPU computing resource); free access to the internal hydra GPU system; free access to the UK supercomputer ARCHER; free access to the Indy multi-core system; and access to meeting rooms. EPCC also contributed in kind 0.07 FTE of an experienced Technical Architect.

The University of Edinburgh has supplied free access to a wiki and Version Control System with associated disk-space for the needs of the project. It has also provided, free of charge, a web development team for a new elaborate multimedia version of the project website, launched in 2016.

What difference did the ERC make?

The ERC has had a major impact on the PI, the various team members, and in terms of group consolidation.

Running an ERC project has been, unquestionably, the high point of my career. I would estimate that it accelerated my own career progress by a factor of three to four in terms of publication rate, and management experience, over the five year duration. Perhaps the most important benefit of ERC funding is that, beyond being a project manager, one has the time to devote to research on an individual level. It is perhaps the ideal experience for the researcher.

It has been, I think, very beneficial to PhD students in the NESS Project to be involved in a directed undertaking with a large supportive team. All PhD students who passed through the NESS Project have academic records closer to the level of postdoctoral fellows; and indeed, this is not surprising, given the ERC ethos. Thus, even for junior researchers, ERC funding has made a very large difference.

The benefit to the immediate research environment has been incalculable; this is covered in the relevant section in this report.

How many people completed a PhD in the	3

framework of the project?	
Comments:	Three completions, all with PI as main supervisor. Craig Webb (2014, cosupervised with Alan Gray, EPCC) Alberto Torin (2015, cosupervised with Cyril Touze, ENSTA Palaiseau) Brian Hamilton (2016, cosuprvised with Lauri Savioja, Aalto University Helsinki)
How many people started a PhD in the framework of the project?	6
Comments:	Three students have graduated, and a further three are in progress: Reginald Harrison, due to finish in 2017. Charlotte Desvages, due to finish in 2017. Larisa Stoltzfus, due to finish in 2019.

List of free Keywords

acoustics, musical acoustics, room acoustics, architectural acoustics, building acoustics, computational acoustics, nonlinear acoustics, linear acoustics, acoustic engineering, audio engineering, audio signal processing, digital signal processing, sound synthesis, physical models, physical modeling, physical modeling synthesis, computer music, numerical methods, time stepping methods, Hamiltonian numerical methods, implicit methods, GPU, multicore, parallel computation

Annex: Project output records

A1. Publications

LIST OF SCIENTIFIC PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES												
No.	Title / DOI	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Does the article acknowledge ERC funding?	Is open access provided to this publication ?	Type	URL
1	A digital waveguide-based approach for Clavinet modeling and synthesis	Leonardo Gabrielli , Vesa Välimäki , Henri Penttinen , Stefano Squartini , Stefan Bilbao	Eurasip Journal on Advances in Signal Processing	Vol. 2013/Issue 1	Springer Publishing Company		13/05/2013	103	Yes	Yes	Peer reviewed	http://asp.eura?sipjournals.spr?ingeropen. com/a?rticles/10.1186?/1687-6180-2013?-103
2	Sampling and Reconstruction on a Diamond Grid and the Tetrahedral Digital Waveguide Mesh	Brian Hamilton	IEEE Signal Processing Letters	Vol. 20/Issue 10	Institute of Electrical and Electronics Engineers Inc.	United States	01/10/2013	925-928	Yes	No	Peer reviewed	http://ieeexplo?re.ieee.org/doc?ument/6558 503/
3	Finite difference time domain simulation for the brass instrument bore	Stefan Bilbao , John Chick	Journal of the Acoustical Society of America	Vol. 134/Issue 5	Acoustical Society of America	United States	01/01/2013	3860	Yes	No	Peer reviewed	http://scitatio?n.aip.org/conte?nt/asa/journal/?jasa/134/5/10.1?121/1.4822479
4	Physical Modeling of Timpani Drums in 3D on GPGPUs	Stefan Bilbao, Craig Webb	AES: Journal of the Audio Engineering Society	61/10	Audio Engineering Society		01/10/2013	737-748	Yes	No	Peer reviewed	http://www.aes.?org/e-lib/brows?e.cfm?el
5	Dynamics of the wave turbulence spectrum in vibrating plates: A numerical investigation using a conservative finite difference scheme	Michele Ducceschi , Olivier Cadot , Cyril Touzé , Stefan Bilbao	Physica D: Nonlinear Phenomena	Vol. 280-281	Elsevier	Netherlands	01/07/2014	73-85	Yes	No	Peer reviewed	http://linkingh?ub.elsevier.com?/retrieve/pii/S?016727891400087?6
6	Numerical Modeling of Collisions in Musical Instruments	S. Bilbao , A. Torin , V.	Acta Acustica united with Acustica	Vol. 101/Issue	S. Hirzel Verlag GmbH	Germany	01/01/2015	155-173	Yes	No	Peer reviewed	http://openurl.?ingenta.com/con?tent/xre

		Chatziioannou		1								f? genre?=article&issn=1?610-1928&volume?=101 &issue=1&sp?age=155
7	Modeling of Complex Geometries and Boundary Conditions in Finite Difference/Finite Volume Time Domain Room Acoustics Simulation 10.1109/TASL. 2013.2256897	Stefan Bilbao	IEEE Transactions on Audio, Speech and Language Processing	Vol. 21/Issue 7	Institute of Electrical and Electronics Engineers Inc.	United States	01/07/2013	1524-1533	Yes	No	Peer reviewed	http://ieeexplo?re.ieee.org/lpd?ocs/epic03 /wrap?per.htm?arnumbe?r=6494263
8	Conservative numerical methods for the Full von Kármán plate equations	Stefan Bilbao , Olivier Thomas , Cyril Touzé , Michele Ducceschi	Numerical Methods for Partial Differential Equations	Vol. 31/Issue 6	John Wiley and Sons Inc.	United States	01/11/2015	1948-1970	Yes	No	Peer reviewed	http://doi.wile?y.com/10.1002/n?um. 21974
9	Numerical Modeling and Sound Synthesis for Articulated String/Fretboard Interactions	Stefan Bilbao , Alberto Torin	AES: Journal of the Audio Engineering Society	Vol. 63/Issue 5	Audio Engineering Society	United States	02/06/2015	336-347	Yes	No	Peer reviewed	http://www.aes.?org/e-lib/brows?e.cfm?elib =1763?9
10	Passive models of viscothermal wave propagation in acoustic tubes	Stefan Bilbao , Reginald Harrison , Jean Kergomard , Bruno Lombard , Christophe Vergez	Journal of the Acoustical Society of America	Vol. 138/Issue 2	Acoustical Society of America	United States	01/08/2015	555-558	Yes	No	Peer reviewed	http://asa.scit?ation.org/doi/1?0.1121/1.4 92640?7
11	An Environment for Physical Modeling of Articulated Brass Instruments	Reginald Langford Harrison , Stefan Bilbao , James Perry , Trevor Wishart	Computer Music Journal	Vol. 39/Issue 4	MIT Press Journals	United States	01/12/2015	80-95	Yes	No	Peer reviewed	http://www.mitp?ressjournals.or?g/doi/10.1162/C?OMJ_a_00332
12	Finite Volume Time Domain Room Acoustics Simulation under General Impedance Boundary Conditions	Stefan Bilbao , Brian Hamilton , Jonathan Botts , Lauri Savioja	IEEE Transactions on Audio, Speech and Language Processing	Vol. 24/Issue 1	Institute of Electrical and Electronics Engineers Inc.		01/01/2016	161-173	Yes	No	Peer reviewed	http://ieeexplo?re.ieee.org/doc?ument/7327 143/
13	Wave-based Room Acoustics Simulation: Explicit/Implicit Finite	Stefan Bilbao and Brian	AES: Journal of the Audio Engineering Society	In press	Audio Engineering Society		01/01/2017	12	Yes	No	Peer reviewed	

	Volume Modeling of Viscothermal Losses and Frequency-dependent Boundaries	Hamilton										
14	Linear stiff string vibrations in musical acoustics: Assessment and comparison of models	Michele Ducceschi , Stefan Bilbao	Journal of the Acoustical Society of America	Vol. 140/Issue 4	Acoustical Society of America	United States	01/10/2016	2445-2454	Yes	No	Peer reviewed	http://asa.scit?atio n.org/doi/1?0.1121/1 .4 96255?3
15	Passive time-domain numerical models of viscothermal wave propagation in acoustic tubes of variable cross section	Stefan Bilbao , Reginald Harrison	Journal of the Acoustical Society of America	Vol. 140/Issue 1	Acoustical Society of America	United States	01/07/2016	728-740	Yes	No	Peer reviewed	http://asa.scit?atio n.org/doi/1?0.1121/1 .4 95902?5
16	Two-Polarisation Physical Model of Bowed Strings with Nonlinear Contact and Friction Forces, and Application to Gesture-Based Sound Synthesis 10.3390/app60 50135	Charlotte Desvages , Stefan Bilbao	Applied Sciences	Vol. 6/Issue 5	MDPI AG, Applied Sciences Editorial Office, Klybeckstrasse 64, 4057 Basel, Switzerland	Switzerland	01/05/2016	135	Yes	Yes	Peer reviewed	http://www.mdpi ?.com/2076-3417 /?6/5/135
17	Aliasing Reduction in Clipped Signals 10.1109/TSP.2 016.2585091	Fabian Esqueda , Stefan Bilbao , Vesa Valimaki	IEEE Transactions on Signal Processing	Vol. 64/Issue 20	Institute of Electrical and Electronics Engineers Inc.	United States	15/10/2016	5255-5267	Yes	No	Peer reviewed	http://ieeexplo?re.i eee.org/doc?ument/74 99 828/
18	A modal-based approach to the nonlinear vibration of strings against a unilateral obstacle: simulations and experiments in the pointwise case	Clara Issanchou, Stefan Bilbao, Jean-Loic LeCarrou, Cyril Touze, Olivier Doare	Journal of Sound and Vibration	In Press	Academic Press Inc.		01/01/2017	0-0	Yes	No	Peer reviewed	
19	Antiderivative Antialiasing for MemorylessNonlinearities	Stefan Bilbao, Fabian Esqueda, Julian Parker and Vesa Valimaki	IEEE Signal Processing Letters	in press	Institute of Electrical and Electronics Engineers Inc.		01/03/2017	0-0	Yes	No	Peer reviewed	
	Finite Difference Schemes in Musical Acoustics: A Tutorial	S. Bilbao, B. Hamilton, R. Harrison and A. Torin	Handbook of Systematic Musicology		Springer	Heidelberg, Germany	01/01/2018	54	Yes	No	Artic le	
	Timpani Drum Synthesis in 3D on GPGPUs	S. Bilbao and C. Webb	Proceedings of the 15th International Conference on		University of York	York, UK	17/09/2012		Yes	Yes	Confe rence	

			Digital Audio Effects									
	Binaural Simulations Using Audio Rate FDTD Schemes and CUDA	C. Webb and S. Bilbao	Proceedings of the 15th International Conference on Digital Audio Effects		University of York	York, UK	17/09/2012		Yes	Yes	Confe rence	
	Construction and Optimization Techniques for High Order Schemes for the 2D Wave Equation	S. Bilbao and B. Hamilton	Proceedings of the 21st International Congress on Acoustics		International Congress on Acoustics	Montreal, Canada	02/06/2013		Yes	No	Confe rence	
	Hexagonal vs. rectilinear grids for explicit finite difference schemes for the two-dimensional wave equation	Brian Hamilton , Stefan Bilbao	Proceedings of the 21st International Congress on Acoustics		ASA		02/06/2013	01512 0-01 5120	Yes	No	Confe rence	http://scitatio?n.aip.org/conte?nt/asa/journal/?poma/19/1/10.11?21/1.4800308
	Large-scale Virtual Acoustics Simulation at Audio Rates Using Three Dimensional Finite Difference Ti	C. Webb and A. Gray	Proceedings of the 21st International Congress on Acoustics		International Congress on Acoustics	Montreal, Canada	02/06/2013		Yes	Yes	Confe rence	
	Modelling Binaural Receivers in Finite Difference Simulation of Room Acoustics	J. Sheaffer, C. Webb and B. Fazenda	Proceedings of the 21st International Congress on Acoustics		International Congress on Acoustics	Montreal, Canada	02/06/2013		Yes	No	Confe rence	
	Large Scale Physical Modeling Sound Synthesis	S. Bilbao, B. Hamilton, A. Torin, C. Webb, P. Graham, A. Gray. K. Kavoussanakis and J. Perry	Proceedings of the 4th Stockholm Musical Acoustics Conference/11th Sound and Music Computing Conference		KTH	Stockholm, Sweden	01/08/2013		Yes	Yes	Confe rence	
	Numerical Experiments with Non-linear Double Membrane Drums	A. Torin and S. Bilbao	Proceedings of the 4th Stockholm Musical Acoustics Conference/11th Sound and Music Computing Conference		KTH	Stockholm	29/07/2013		Yes	Yes	Confe rence	
	ON FINITE DIFFERENCE SCHEMES FOR THE 3-D WAVE EQUATION USING NON-CARTESIAN GRIDS	B. Hamilton and S. Bilbao	Proceedings of the 4th Stockholm Musical Acoustics Conference/11th Sound and Music Computing Conference		KTH	Stockholm, Sweden	29/07/2013		Yes	Yes	Confe rence	
	Computing virtual acoustics using the 3D #nite difference time domain method and Kepler architecture GPUs	C. Webb	Proceedings of the 4th Stockholm Musical Acoustics Conference/11th Sound and Music Computing Conference		KTH	Stockholm, Sweden	29/07/2013		Yes	Yes	Confe rence	

	Numerical Simulation of Spring Reverberation	S. Bilbao	Proceedings of the 16th International Digital Audio Effects Conference		NUI Maynooth	Maynooth, Ireland	02/09/2013		Yes	Yes	Confe rence	
	A 3D Multi-Plate Environment for Sound Synthesis.	A. Torin and S. Bilbao	Proceedings of the 16th International Digital Audio Effects Conference		NUI Maynooth	Maynooth, Ireland	02/09/2013		Yes	Yes	Confe rence	
	Fourth order and Optimised Finite Difference Schemes for the 2D Wave Equation.	B. Hamilton and S. Bilbao	Proceedings of the 16th International Digital Audio Effects Conference		NUI Maynooth	Maynooth, Ireland	02/09/2013		Yes	Yes	Confe rence	
	Room Acoustics Modeling Using GPU-Accelerated Finite Difference and Finite Volume Methods on a Face-Centred Cubic Grid	B. Hamilton and C. J. Webb	Proceedings of the 16th International Digital Audio Effects Conference		NUI Maynooth	Maynooth, Ireland	02/09/2013		Yes	Yes	Confe rence	
	Numerical Modeling of String Barrier Collisions.	S. Bilbao	Proceedings of the International Symposium on Musical Acoustics		ENSIM	LeMans, France	07/07/2014		Yes	Yes	Confe rence	
	Numerical Simulation of String/Barrier Collisions: The Fretboard	S. Bilbao and A. Torin	Proceedings of the 17th International Digital Audio Effects Conference		University of Erlangen	Erlangen, Germany	01/09/2014		Yes	Yes	Confe rence	
	Revisiting Implicit Finite Difference Schemes for Three-Dimensional Room Acoustics Simulations	B. Hamilton, S. Bilbao and C. J. Webb	Proceedings of the 17th International Digital Audio Effects Conference		University of Erlangen	Erlangen, Germany	01/09/2014		Yes	Yes	Confe rence	
	An Energy Conserving Finite Difference Scheme for the Simulation of Collisions in Snare Drums	A. Torin, B. Hamilton and S. Bilbao	Proceedings of the 17th International Digital Audio Effects Conference		University of Erlangen	Erlangen, Germany	01/09/2014		Yes	Yes	Confe rence	
	Finite Difference Schemes on Hexagonal Grids for Thin Linear Plates with Finite Volume Boundaries	B. Hamilton and A. Torin	Proceedings of the 17th International Digital Audio Effects Conference		University of Erlangen	Erlangen, Germany	01/09/2014		Yes	Yes	Confe rence	
	Finite Volume Perspectives on Finite Difference Schemes and Boundary Forumulations for Wave Simulation	B. Hamilton	Proceedings of the 17th International Digital Audio Effects Conference		University of Erlangen	Erlangen, Germany	01/09/2014		Yes	Yes	Confe rence	
	Physical Modeling of Nonlinear Player-String Interactions in BowedString Sound Synthesis Using Finite Difference Methods	C. Desvages and S. Bilbao	Proceedings of the International Symposium on Musical Acoustics		ENSIM	LeMans, France	07/07/2014		Yes	Yes	Confe rence	

	A Single Valve Brass Instrument Model using Finite-Difference Time-Domain Methods	R. Harrison and J. Chick	Proceedings of the International Symposium on Musical Acoustics		ENSIM	LeMans, France	07/07/2014		Yes	Yes	Confe rence	
	Nonlinear Effects in Drum Membranes	A. Torin and M. Newton	Proceedings of the International Symposium on Musical Acoustics		ENSIM	LeMans, France	07/07/2014		Yes	Yes	Confe rence	
	Collisions in Drum Membranes: a preliminary study on a simplifiedsystem	A. Torin and M. Newton	Proceedings of the International Symposium on Musical Acoustics		ENSIM	LeMans, France	07/07/2014		Yes	Yes	Confe rence	
	Non-stationary wave turbulence in elastic plates: a numerical investigation	M. Ducceschi, C. Touze, O. Cadot and S. Bilbao	Proceedings of the European Nonlinear Dynamics Conference		Technische Universitat Wien	Vienna, Austria	06/07/2014		Yes	No	Confe rence	
	Modular Physical Modeling Synthesis Environments on GPU	S. Bilbao, A. Torin, P. Graham, J. Perry and G. Delap	Proceedings of the International Computer Music Conference		University of Athens	Athens, Greece	14/09/2014		Yes	Yes	Confe rence	
	The Changing Picture of Nonlinearity in Musical Instruments	S. Bilbao	Proceedings of the International Symposium on Musical Acoustics		ENSIM	LeMans, France	07/07/2014		Yes	Yes	Confe rence	
	Sound Propagation in Air with ViscothermalLosses using Finite Difference Schemes on GPU	B. Hamilton, S. Bilbao and C. Webb	Proceedings of Forum Acusticum		Polish Acoustical Society	Krakow, Poland	07/09/2014		Yes	No	Confe rence	
	Optimising a Physical Modelling Synthesis Code Using Hybrid Techniques	J. Perry, A. Gray and S. Bilbao	Proceedings of the International Conference on Parallel Computing		University of Edinburgh		01/09/2015		Yes	Yes	Confe rence	
	Aliasing Reduction in Soft Clipping Algorithms	F. Esqueda, V. Valimaki and S. Bilbao	Proceedings of the European Signal Processing Conference		IEEE		31/08/2015		Yes	Yes	Confe rence	http://ieeexplo?re.ieee.org/xpl?/articleDetails?.jsp?arnumber=7?362737
	Two-polarisation finite difference model of bowed strings with nonlinear contact and friction forces	C. Desvages and S. Bilbao	Proceedings of the 18th International Conference on Digital Audio Effects		NTNU		30/11/2015		Yes	Yes	Confe rence	
	An Algorithm for A Valved Brass Instrument Synthesis Environment using Finite-Difference Time-Domain Methods with Performance	R. Harrison, S. Bilbao and J. Perry	Proceedings of the 18th International Conference on Digital Audio Effects		NTNU		30/11/2015		Yes	Yes	Confe rence	

	Optimisation											
	Pushing the Limits: A Real-time Large Scale Modular Synthesis Environment	C. Webb and S. Bilbao	Proceedings of the 18th International Conference on Digital Audio Effects		NTNU		30/11/2015		Yes	Yes	Confe rence	
	Large Stencil Operations for GPU-based 3-D Acoustics Simulations	B. Hamilton, C. Webb, A. Gray and S. Bilbao	Proceedings of the 18th International Conference on Digital Audio Effects		NTNU		30/11/2015		Yes	Yes	Confe rence	
	Finite Volume Modelling of Viscothermal Losses and Frequency-dependent Boundaries in Room Acoustics Applications	S. Bilbao and B. Hamilton	Proceedings of the Audio Engineering Society Conference		AES		02/02/2016		Yes	No	Confe rence	http://www.aes.?org/ e-lib/brows?e.cfm?el ib =1807?9
	Bow control and playability of a two-polarisation time domain physical model of a bowed string	C. Desvages and M. Newton	Proceedings of thee International Symposium on Musical and Room Acoustics		ISMRA	La Plata, Argentina	11/09/2016		Yes	Yes	Confe rence	
	Méthode modale mixte pour le contact unilatéral corde/obstacle: application au chevalet courbé	C. Issanchou, S. Bilbao, O. Doaré, J.-L. Le Carrou, and C. Touzé	Proceedings of the 13e Congrès Français d'Acoustique		Univrsite du Maine	Le Mans, France	11/04/2016		Yes	Yes	Confe rence	
	Controlling complex virtual instruments—A setup with note for Max and prepared piano sound synthesis	T. Resch and S. Bilbao	International Conference on New Instruments for Musical Expression		NIME		11/07/2016		Yes	Yes	Confe rence	
	Passive Time-domain Numerical Designs for Room Acoustics Simulation	S. Bilbao and B. Hamilton	Proceedings of the International Congress on Acoustics		ICA	Buenos Aires, Argentina	05/09/2016		Yes	Yes	Confe rence	
	Antialiased Soft-clipping Using a Polynomial Approximation of the Integrated Bandlimited Ramp Function	F. Esqueda, V. Välimäki and S. Bilbao	Proceedings of the International Congress on Acoustics		ICA	Bunos Aires, Argentina	05/09/2016		Yes	Yes	Confe rence	
	Modelling Collisions of Nonlinear Strings Against Rigid Barriers: Conservative Finite Difference Schemes with Application to Sound Synthesis	M. Ducceschi and S. Bilbao	Proceedings of the International Congress on Acoustics		ICA	Bunos Aires, Argentina	05/09/2016		Yes	Yes	Confe rence	

	Improved Frequency-dependent Damping for Time Domain Modeling of Linear String Vibration	C. Desvages and S. Bilbao	Proceedings of the International Congress on Acoustics		ICA	Buenos Aires, Argentina	05/09/2016		Yes	Yes	Conference	
	Optimisation Techniques for Finite Order Viscothermal Loss Modeling in Acoustic Tubes	S. Bilbao and R. Harrison	Proceedings of the International Symposium on Musical and Room Acoustics		ISMRA	La Plata, Argentina	11/09/2016		Yes	Yes	Conference	
	Compact explicit finite difference schemes using a 25-point stencil for the three-dimensional acoustical wave equation	B. Hamilton and S. Bilbao	Proceedings of the International Congress on Acoustics		ICA	Buenos Aires, Argentina	05/09/2016		Yes	Yes	Conference	
	Eliminating aliasing caused by discontinuities using integrals of the sinc function	F. Esqueda, V. Välimäki and S. Bilbao	Proceedings of the International Symposium on Musical and Room Acoustics		ISMRA	La Plata, Argentina	11/09/2016		Yes	Yes	Conference	
	Comments on Travelling Wave Solutions in Nonlinear Acoustic Tubes: Application to Musical Acoustics	R. Harrison and S. Bilbao	Proceedings of the International Congress on Acoustics		ICA	Buenos Aires, Argentina	05/09/2016		Yes	Yes	Conference	
	Coupling of a One-dimensional Acoustic Tube to a Three-dimensional Acoustic Space Using Finite Difference Time-domain Methods	R. Harrison and S. Bilbao	Proceedings of the International Symposium on Musical and Room Acoustics		ISMRA	La Plata, Argentina	11/09/2016		Yes	Yes	Conference	
	Rounding Corners with BLAMP	F. Esqueda, V. Välimäki and S. Bilbao	Proceedings of the 19th International Conference on Digital Audio Effects		University of Brno	Brno, Czech Republic	05/09/2016		Yes	Yes	Conference	
	A Modal Approach for the Numerical Simulation of a String Vibrating Against and Obstacle: Application to Sound Synthesis	C. Issanchou, J.-L. LeCarrou, S. Bilbao, C. Touzé and O. Doaré	Proceedings of the 19th International Conference on Digital Audio Effects		University of Brno	Brno, Czech Republic	05/09/2016		Yes	Yes	Conference	
	Antialiased Soft Clipping using an Integrated Bandlimited Ramp Function	F. Esqueda, V. Välimäki and S. Bilbao	Proceedings of the European Signal Processing Conference		IEEE		29/08/2016		Yes	Yes	Conference	
	Finite Difference Room Acoustics Simulation with General Impedance Boundaries and Viscothermal Losses	B. Hamilton C. Webb, S. Bilbao and N.	Proceedings of the International Symposium on Musical and Room Acoustics		ISMRA	La Plata, Argentina	11/09/2016		Yes	Yes	Conference	

	in Air: Parallel Implementation on Multiple GPUs	Fletcher										
	Parallel computation techniques for virtual acoustics and physical modelling synthesis	C. Webb			University of Edinburgh	Edinburgh, UK	15/05/2014		Yes	Yes	Thesis	
	Percussion Instrument Modelling In 3D: Sound Synthesis Through Time Domain Numerical Simulation	Alberto Torin			University of Edinburgh		20/11/2015		Yes	Yes	Thesis	
	Finite Difference and Finite Volume Methods for Wave-based Modelling of Room Acoustics	Brian Hamilton			University of Edinburgh	Edinburgh, UK	08/04/2016		Yes	Yes	Thesis	

A2. Research expeditions

List of expeditions		
Period (start-end)	Place	Purpose

A3. Awards and recognitions

List of awards and recognitions					
Award type	Title of the award	Person to whom the award was made	Year	Short description of the reason the award was made (if applicable)	Any further information / clarification
Research Prize / Research Medal	Best paper award	Stefan Bilbao and Craig Webb	2012	Best paper (1 of 3) at the International Conference on Digital Audio Effects, York, UK, September 2012.	
Fellowship / membership of learned society	Emil Torick Scholarship	Charlotte Desvages	2014	Audio Engineering Society Educational Foundation: top award, worldwide, for 2014.	
Other	Keynote Lecture	Stefan Bilbao	2014	Keynote lecture at the International Symposium	Le Mans, France

				on Musical Acoustics	
Other	Keynote Lecture	Stefan Bilbao	2012	Keynote lecture, Journee des Jeunes Chercheurs en Acoustique, Audio et Son	Marseille, France
Other	Keynote Lecture	Stefan Bilbao	2015	Keynote Lecture, Sound and Music Computing Conference	Maynooth, Ireland (upcoming)
Research Prize / Research Medal	Best paper award	Stefan Bilbao and Alberto Torin	2014	Best paper award at the 17th International Conference on Digital Audio Effects, Erlangen Germany, September 2014.	
Research Prize / Research Medal	Best paper	Charlotte Desvages and Stefan Bilbao	2015	Best paper at the 18th International Conference on Digital Audio Effects, Trondheim, Norway	

A4. Patents, licensing, intellectual property

List of patents, licensing, intellectual property					
Type of IP Rights	Confidential	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant(s) (as on the application)

A5. Dissemination to non-academic audience

List of disseminations								
No.	Type of activities	Main Leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
1	Presentations	THE UNIVERSITY OF EDINBURGH	Large Scale 3D Audio Rendering	07/05/2014	University of Edinburgh	Scientific community (higher education, Research) - Civil society - Medias	100	United Kingdom

A6. Other significant outputs / information

Information on other important outputs which have arisen - wholly or partly - from this project.

In an interdisciplinary project such as NESS, there are various types of outputs beyond printed publications. These may be grouped as follows:

1) Musical Pieces and Performances:

Through the course of NESS, we have had approximately 15 visits from composers to work directly with the NESSGPU system. Many of these visits resulted in completed pieces of music, usually in a multichannel format. These have been performed on multiple occasions worldwide. To date, six pieces have been completed, and are listed below, along will all performances. All are in the process of being made freely available on YouTube, and are linked from the NESS page at

http://www.ness.music.ed.ac.uk/music-and-tools/music

Untitled, G. Sassoon, December, 2016. Stereo, 3 minutes.

From Inner to Outer Shadow, G. Delap, December, 2016. Stereo, 4 minutes

Collision Suite, G. Sassoon, July, 2016. 8 channels.
Performances:
2016 – Institut de Recherche et Coordination Acoustique/Musique, Paris, France

Black Dog, G. Delap, April 2016. 32 channels.
Performances:
2016 – Institut de Recherche et Coordination Acoustique/Musique, Paris, France
2016 – IX Symposium, Montreal, Canada
2016 – Directions Concert Series, Dublin, Ireland

Dithyramb-Kepler 63e, T. Wishart, March-August 2014. 8 Channels.
Performances:
2016 – Beyond Techno, Tempo Reale, Florence, Italy
2016 – De Koffie Fabriek, Amsterdam, the Netherlands
2016 – Arnold Schonberg Zaal of the Royal Conservatory, Den Haag, the Netherlands

2016 – Institut de Recherche et Coordination Acoustique/Muusique, Paris, France
2015 – AKOUSMA series, Multiphonie 15/16 cycle, of the INA/GRM, Paris, France
2015 – d'Bâle Festival, Haus der Elektronischen Künste, Basel, Switzerland
2015 – Hochschüle für Musik Franz Liszt, Weimar, Germany
2015 – Logos Foundation, Gent, Belgium
2015 – MUSLAB, Memorial auditorium, Centro de Cultura Digital, Mexico City, Mexico
2015 – MUSLAB, Centro Cultura Recoleta, Buenos Aires, Argentina
2015 – International Festival for Innovations in Music Production and Composition, Leeds, UK
2015 – Octaphonic Event at Swansea University Trinity of St David's, Swansea, UK
2015 – 12th Sound and Music Computing Conference, Maynooth, Ireland
2014 – Jacqueline du Pré Concert Hall, St Hilda's College, Oxford, UK
2014 – Royal Conservatory, Den Haag, the Netherlands
2014 – Musicon Concert Series, Durham Town Hall, Durham, UK

Ashes to Ashes, G. Delap, November, 2013. 16 channels
Performances:
2016 – Institut de Recherche et Coordination Acoustique/Musique, Paris, France
2015 – 12th Sound and Music Computing Conference, Maynooth, Ireland
2015 – Contemporanea Music Festival, Udine, Italy
2015 – Not a Concert, Edinburgh, UK
2013 – Center for Computer Research in Music and Acoustics, Stanford University, Stanford, USA

2) Project website

The NESS Project website, at www.ness-music.eu, was completely overhauled over the course of 2016, and is live as of December 2016. It is comprehensive, and contains a) a full list of all NESS publications, downloadable when permitted, b) a list of all completed music, plus links to YouTube, c) various tutorial sections, including approximately 100 illustrative videos and sound examples.

3) Instructional videos

A series eight videos describing the NESS Project in its entirety, and led by various members of staff as well as visiting musicians, was professionally produced by the University of Edinburgh, through additional funding supplied by the Edinburgh College of Art. The videos are available at https://www.youtube.com/playlist?list=PLwF_PUjl-StIByQYUCpWmfXyRCldl4iKb

4) Web-based synthesis service

From late 2012, the Edinburgh Parallel Computing Centre has hosted a web-based service, allowing remote use of the NESSGPU system; it has been used by all the visiting musicians, who must be registered through the University of Edinburgh Authentication Service. All of the synthesis codes developed under the NESS Project are available for remote use, free of charge. The Web-based synthesis service acknowledges ERC support in its front-page.

5) Software releases

In addition to codes running on the web-based service, for some smaller scale codes, standalone versions are available for download. One example is the brass synthesis package, developed by RH and JP, in conjunction with the PI. Commercial applications, for systems which approach real time performance are under development. A plate reverberation unit, designed by MD has been ported to real time by CW, and a beta release will occur in early 2017. A version of the NESS net1 modular environment is also in the final stages of being ported by CW. Both real time applications will be released by the spinout company Physical Audio: http://www.physicalaudio.co.uk/

(Only for ERC projects selected from the 2012 and 2013 calls for proposals)

This grant agreement includes special clause 39, requiring you to make best efforts towards open access to publications resulting from this project. Should, despite your best efforts, not all publications be available in open access, please give reasons why this is the case.

Attachments	
Project No.:	279068
Project acronym:	NeSS
Project title:	Listening to the Future: Next-generation Sound Synthesis ?through Simulation
Project starting date:	01/01/2012
Project duration:	60
Principal Investigator name:	Dr. Stefan Bilbao
Report submitted by:	THE UNIVERSITY OF EDINBURGH
Date:	